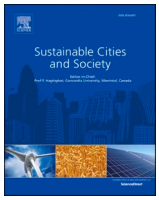
Sustainable Cities and Society 75 (2021) 103268

Contents lists available at ScienceDirect

Sustainable Cities and Society

journal homepage: www.elsevier.com/locate/scs



Reducing non-residential asset sanitisation water footprint for improved public health in water-deficient cities

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ARTICLE INFO

Keywords:
freshwater
Public health
Sanitisation
Water footprint
UVGI

ABSTRACT

This paper evaluates the potential for reconfiguring city-scale clean water demand by reducing the non-residential asset sanitsation water footprint. A novel methodological framework is proposed for assessing the feasibility of a mix of three surface sanitisation measures (Manual surface wiping, Mechanical cleaning/Rapid disinfectant spraying, Ultraviolet germicidal irradiation-UVGI treatment) in terms of a Sanitisation water-footprint index (SWI); three typical application scenarios are considered – high risk-high frequency, moderate risk-moderate frequency, moderate risk-low frequency. The UVGI treatment outperforms the other two surface treatment methods, particularly in high risk-high frequency scenario in the healthcare setting, with SWI as low as 2%. Further, case-study evidence from a ward-level spatial analysis using real-world data estimates SWI ranging between 0-30% in those wards with greater commercial/public assets, showing clear merit of this framework in re-configuring city-scale public health sanitisation water footprint. A cost-benefit analysis (involving resources – staffing, water and chemicals; capital expenditure, and energy costs) shows superior performance of UVGI treatment over the other two methods from the second year onwards, surpassing the initial cost-effectiveness for corresponding manual or mechanical cleaning. Wider implementation of this framework can foster strategic transformation of city-scale water footprint, which is deemed essential for ensuring sustainable growth of water deficient cities globally.

1. Introduction

The two-prong approach adopted by several countries for returning to economic normalcy amidst the prevalent COVID-19 (Corona Virus Infectious Disease – 2019) public health crisis is posing huge demand on water-based sanitisation, requiring contingency planning for a sustainable sanitisation protocol. Cities are specifically faced with an enormous task of frequently sanitising non-residential assets, including healthcare facilities, public transits, institutions/offices and commercial premises, the latter towards restoring of routine business operations in the city centres (Gude & Muire 2021). A study of 500 cities in the US identified the urgency of recognising water access as a public health priority, especially in those cities with more income inequality (Warner et al. 2020). Typically for water-deficient cities, this leads to a dilemma in sustaining high standard of sanitising public premises at a cost of reduced water supply to meet the water, sanitation and hygiene (WaSH) requirements in the domestic sector. It is estimated that approximately 2 billion people globally, mostly city dwellers, lacked basic handwashing access in 2019, even before the onset of the COVID-19 pandemic (Schmidt 2020). Specifically, COVID-19 has adversely impacted city-residents in slums/informal settlements who are more vulnerable due to acute water shortages (Feldman 2020; Ghosh et al. 2020). Future outbreak preparedness and response plans need to consider both near-term and long-term scenarios for sustained clean water access through innovative processes and strategies (Gude & Muire 2021).

Common disinfection technologies for expiratory/respiratory viruses include ultraviolet germicidal irradiation (UVGI), electrostatic spraying, disinfectant fogging, ozone generators, plasma, photocatalytic disinfection, heat sterilization, etc. (Chen & O'keeffe 2020). However, the majority of these are applied for inactivation of viruses circulating in the air (Bu et al. 2021). To date, surface disinfection of large facilities is mainly conducted through chlorination, which leads to a huge demand on water and heavy reliance on the supply chain of disinfectant grade chemicals (such as 70% ethanol or sodium hypochlorite) (Water Research Australia 2020). Other effective disinfectants include commercially available quaternary ammonium compounds, such as

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https://doi.org/10.1016/j.scs.2021.103268
Received 11 May 2021; Received in revised form 10 August 2021; Accepted 12 August 2021
Available online 15 August 2021
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cetylpyridinium chloride, used according to manufacturer's instructions, and peracetic or peroxyacetic acid at concentrations of 500−2000 mg/l (Rutala & Weber 2019). Automated room disinfection with hydrogen peroxide vapor has shown promising results in targeting specific microorganisms, albeit with huge chemical demands (Mann et al. 2014). However, frequent exposure to disinfecting chemicals can potentially lead to respiratory illness, asthma, allergy, and other hazardous effects (Rai et al. 2020).

WHO has developed cleaning and disinfection recommendations to mitigate the potential of COVID-19 transmission on environmental surfaces (WHO 2020a), which are basically split into two broad settings (**Figure 1**). In healthcare settings, environmental surfaces include the surfaces of furniture and other fixed items (e.g. tables, chairs, walls, light switches, computer peripherals), as well as the surfaces of non-critical medical equipment (equipment that only comes into contact with intact skin, such as blood pressure cuffs, wheelchairs, incubators). These surfaces should be frequently cleaned with water and detergent, followed by application of a disinfectant. In non-healthcare settings, environmental surfaces include furniture and other fixed items, such as counter tops, stairway rails, as well as floors and walls.

UVGI treatment for surface sanitisation of respiratory viruses as an alternative to water-based treatment holds potential for significant savings of water and chemical resources (S. Miller et al. 2013). UVGI treatments have been identified as a resource-efficient alternative to sterilise public transit and a larger space or room in order to stop COVID-19 spread through disinfection of foamites and aerosols (WHO 2020b). For surfaces, UV-C lamp devices and systems (UVGI-C, 254 nm) have seen increased use in disinfecting hospital rooms through mobile human- or robotic-operated devices (Ackerman 2020; McGinn et al. 2020); air-handling systems and in room settings for the purpose of air and surface disinfection by inactivating viral, bacterial, and fungal organisms from replication (Raeiszadeh & Adeli 2020). Disinfection of buses in China through a combination of UVGI tunnels, and portable UVGI lights placed in vehicles, is reported to reduce the entire vehicle disinfection times by 75% from the original forty minutes using traditional spray and wipe methods (Corbishley 2020; Sustainable Bus 2020).

This paper presents an evaluation of the implementation potential of UVGI-based sanitisation of non-residential assets in order to improve the sanitisation-related water footprint in water-deficient cities. This could be applicable during public health emergencies and as a long-term strategic planning measure. The premise of our study is that with ever increasing urban population, current trends in water-based sanitisation offers limited scope for meeting city-wide water demand, unless a major intervention is implemented to reduce the water-based sanitisation demands of non-residential assets. As a first step, a methodological framework is proposed incorporating the current practice of non-residential (mainly public premises) sanitisation using manual/mechanical cleaning and UVGI-based sanitisation, the latter for substituting large volume of chemical and water resources applied in disinfecting those public assets where risk of human exposure is negligible. Given the unexplored nature of the solution, the feasibility of this framework is demonstrated through a combination of hypothetical scenarios and a dedicated case study using spatial analysis, based on real-world sanitisation demands for a megalopolis. Spatial analysis of the proposed intervention is applied to estimate the reduced water-based sanitisation of non-residential assets at ward-level. Relevant inferences drawn from this case study at the resource-energy nexus and their policy implications are discussed. A cost-benefit assessment is presented thereafter, comparing the performance of UVGI treatment with manual surface wiping and mechanical cleaning (using a rapid disinfectant sprayer). Finally, the limitations of the UVGI treatment and some future recommendations are presented.

2. Framework development for city-scale non-residential surface sanitisation

An adaptive framework for city-wide operation of public premises sanitisation (such as healthcare facilities, transport hubs and institutions/workplaces) is presented in this section. This is primarily motivated to reconfigure drinking water distribution system with increased provision of reliable, freshwater access to the domestic sector in order to combat future public health crisis. Alongside the resilience

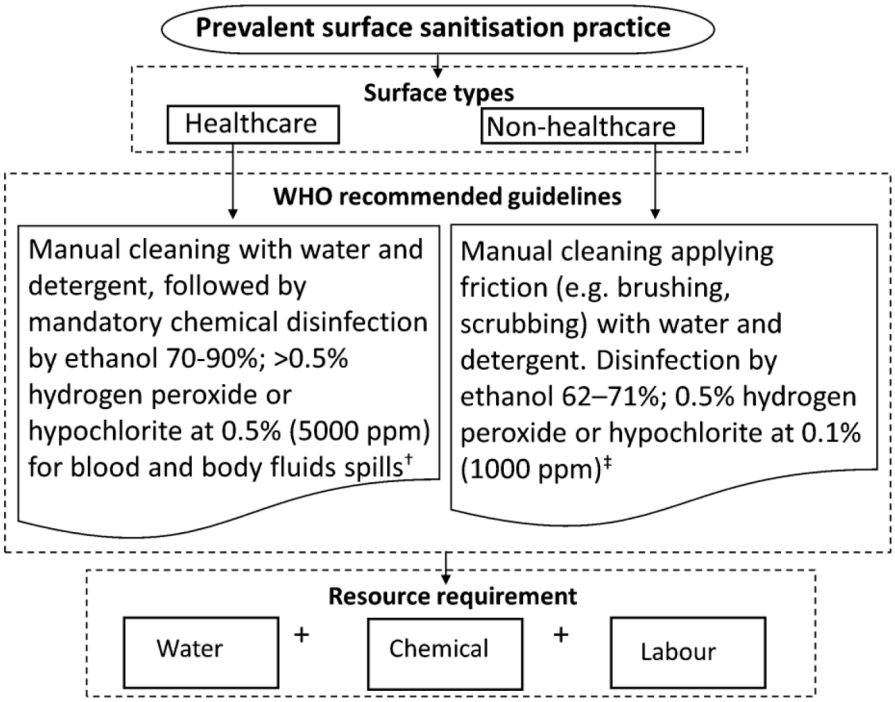
Prevalent surface sanitisation practice
Surface types
Healthcare
Non-healthcare
WHO recommended guidelines
Manual cleaning with water and detergent, followed by mandatory chemical disinfection by ethanol 70-90%; >0.5% hydrogen peroxide or hypochlorite at 0.5% (5000 ppm) for blood and body fluids spills†
Manual cleaning applying friction (e.g. brushing, scrubbing) with water and detergent. Disinfection by ethanol 62–71%; 0.5% hydrogen peroxide or hypochlorite at 0.1% (1000 ppm)‡
Resource requirement
Water
+
Chemical
+
Labour

Figure 1. Prevalent water-based surface sanitisation protocols
†(Kampf et al. 2020)
‡(Rutala & Weber 2014)

introduced by the intervention proposed in this framework in meeting water demands in a future pandemic-like situation, these drivers could also transform the current practice of public premises sanitisation as part of long-term strategic planning. This can avoid investment pressures in costly infrastructure projects to mitigate perennial water shortages from the dilemma of non-residential asset sanitisation vs. domestic freshwater demand in evergrowing cities.

The first step in the framework determines appropriate combination of sanitisation options based on risk-based prioritisation, using the following hierarchical steps (Figure 2)

- operational characteristic (hours of operation and human presence);
- size and shape of the area to be treated, and how easily it can be sealed off while delivering an airborne product;
- whether there are hard or soft surfaces (e.g. soft furnishings may act as a 'sink' for the airborne chemicals and emit them for a period of time after treatment);
- spatial configuration/floor plan and accessibility of the surface to be treated (e.g. horizontal stretch). This is primarily to ascertain whether there is ample floor space suitable for UVGI treatment. In some small spaces, UVGI treatments may not be suitable if the units need to be placed at a minimum distance from walls etc. to be deployed safely.

The hierarchical conditional steps in the framework determine which of the three methods of surface sanitisation could be the most applicable in a given setting. In the next step, the feasibility of a mix of different sanitisation practices for a given scenario is assessed in terms of a 'Sanitisation waterfootprint index (SWI)', which is formulated as the ratio of the total water demand for the modified practice to that of the original practice (Eq. (1)).

$$SWI = \frac{\sum Cleaning_{optimised} + Disinfection_{optimised} + Sterilisation_{UV}}{\sum Cleaning_{water-based} + Disinfection_{water-based} + Sterilisation_{Chemical}} x100 \quad (1)$$

It is noteworthy, the $Sterilisation_{UV}$ is a notional term in the equation representing the offset to the actual water demand through UV treatment. Therefore, SWI can range between 0-100% (lower score representing more aggressive application of UVGI-based sanitisation, leading to reduced water demand from the corresponding intervention; >50% considered as the threshold for tipping the sustainability balance). The final step involves extending the indicator score to a spatial analysis using ward-level activity volume for three different public asset categories – 1. Healthcare facilities; 2. Commercial buildings; 3. Public transit (rail, metro, and bus). This is meant to facilitate informed decision choices on suitable surface sanitisation alternatives over its performance life-time taking into account their environmental costs (water

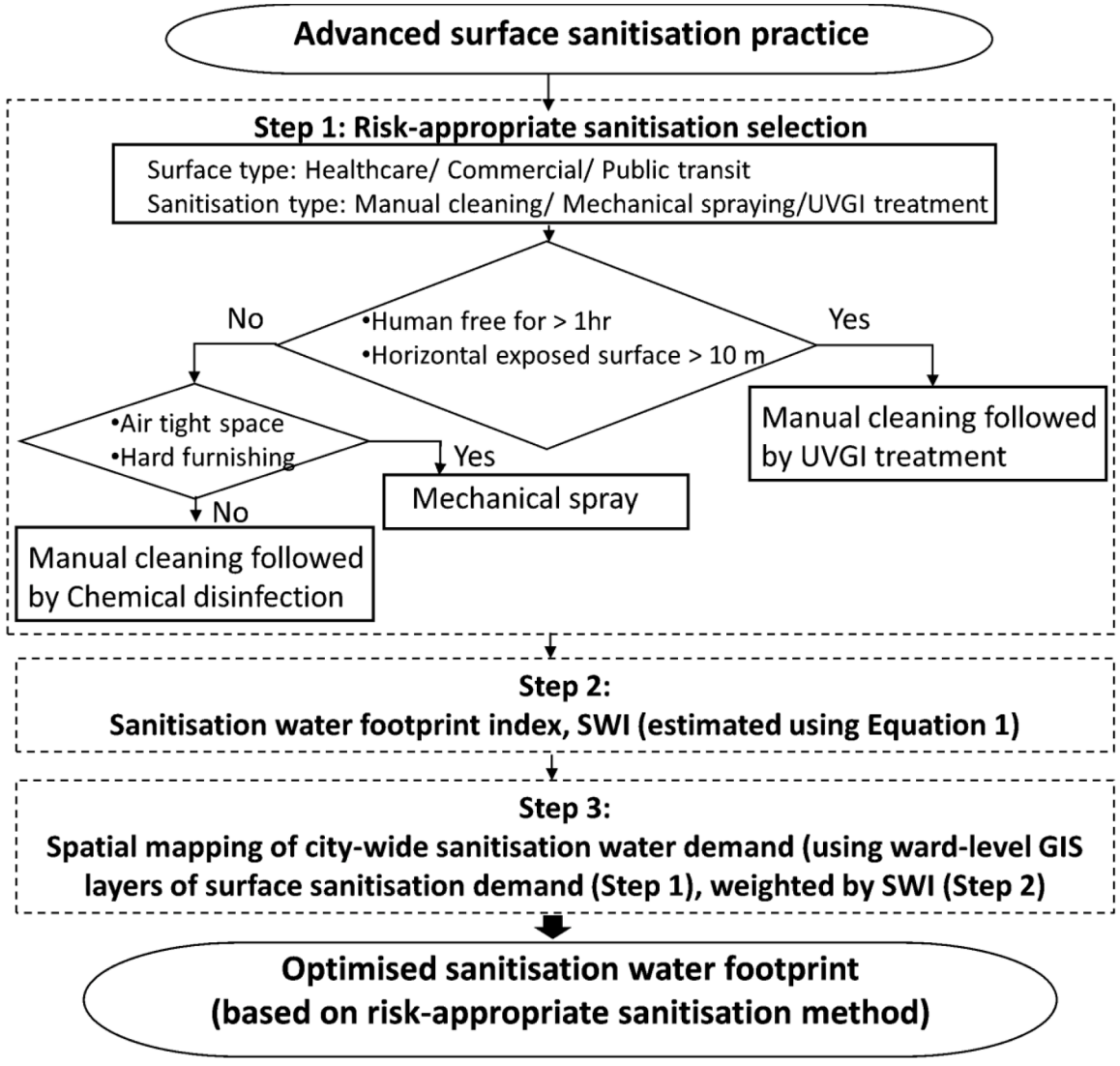
Advanced surface sanitisation practice
Step 1: Risk-appropriate sanitisation selection
Surface type: Healthcare/ Commercial/ Public transit
Sanitisation type: Manual cleaning/ Mechanical spraying/UVGI treatment
•Human free for > 1hr
•Horizontal exposed surface > 10 m
No
Yes
Manual cleaning followed by UVGI treatment
•Air tight space
•Hard furnishing
Yes
No
Mechanical spray
Manual cleaning followed by Chemical disinfection
Step 2:
Sanitisation water footprint index, SWI (estimated using Equation 1)
Step 3:
Spatial mapping of city-wide sanitisation water demand (using ward-level GIS layers of surface sanitisation demand (Step 1), weighted by SWI (Step 2)
Optimised sanitisation water footprint
(based on risk-appropriate sanitisation method)

Figure 2. Framework for assessing city-scale public asset sanitisation water footprint integrating UVGI-based treatment system.

and energy savings), going beyond the short-term gains over the installation phase of UVGI-based treatment system.

Typical disinfection activities considered in this framework could be classified into the following risk-appropriate categories – "High risk-High frequency", "Moderate risk-Moderate frequency", "Moderate risk-Low frequency". Exemplar hypothetical and real-world scenarios and settings for each of these are presented in Section 4 (Tables 2 and 3 respectively).

3. Demonstration Case study

3.1. Site description

Mumbai is one of the largest and the most densely populated urban agglomerations in the world, located on the western coast of the Indian peninsula (18.9404° N, 72.8345° E). Greater Mumbai is divided into 24 wards for administrative purposes, among six zones. Of these, nine are city wards, six are eastern suburb wards, and the remaining nine are western suburb wards (see **Appendix 1, Table S1**) (Municipal Corporation of Greater Mumbai 2020). Over 40% of its households live in slums, where provision of uninterrupted piped water has been a big challenge due to high infrastructure investment needs and depleting water resources leading to inadequate sanitary and drinking water facilities in unhygienic conditions. In some seasons, 95% of households use less than the World Health Organisation (WHO) recommended minimum water consumption of 50 litres per capita per day (Safe water network 2016).

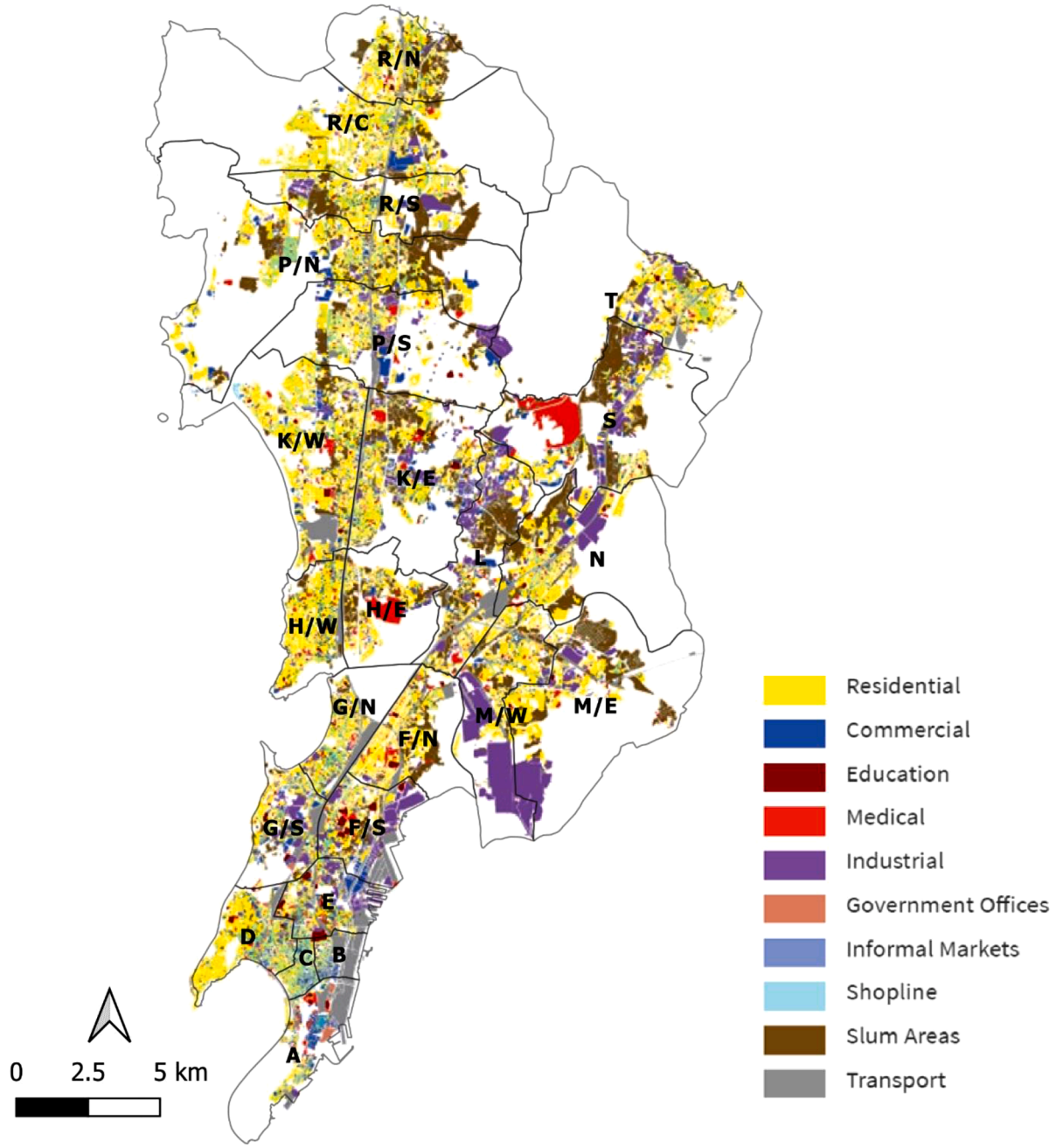

Figure 3. Ward-level spatial distribution of the residential, commercial, medical and educational facilities across Mumbai (Raw data provided in Table S1; data source: Municipal Corporation of Greater Mumbai 2020).

3.2. Data acquisition

Publicly available data from the Municipal Corporation of Greater Mumbai (MCGM) on land use, population and other relevant data sets were used to anayse the total water demand and the water saving potential from replacement of conventional sanitisation using the proposed UVGI treatment. The non-residential settings scoped in this study include educational institutions (both schools and higher education), hospitals, transport hubs, commercial/industrial premises (Safe water network 2016) and public transportation (buses, suburban trains, mono rail). **Figure 3** shows the spatial extent of these structures as a Geographical Information System mapping (GIS) layer plotted using open source Quantum GIS (QGIS v3.14); the raw data is presented in **Appendix 1, Table S1**. The volume of transport fleet is acquired from varios sources, as shown in **Table 1**. Data triangulation was done from the above data sources to provide insights for the situation in Mumbai in order to provide data-informed discussion for decision-making. Asumptions applied to estimation of treated surfaces is provided as footnote to this table.

As noted from **Figure 3** (and **Table S1**), Mumbai has large numbers of commercial complexes, and transport hubs in the southern wards and higher slum pupulations in some of the central, eastern and northern wards.

4. Results and discussion

4.1. Framework evaluation

Table 2 presents a scoping assessment of the implementation potential of the proposed framework in a number of hypothetical scenarios prior to its full-scale implementation in the case study scenario. The scenarios were broadly classified into the following three categories – high risk-high frequency; moderate risk-moderate frequency; moderate risk-low frequency. It shows the varying SWI scores that can be achieved for disinfecting identical surfaces (1000 m^2) in different settings, depending on the risk-appropriate conditions set out in **Figure 2**. The corresponding SWI for each scenario is estimated based on the water saving potential (where applicable) through equivalent UVGI treatment using the water-based sanitisation protocols (shown in the footnote of Table 2). As expected, the SWI for the setting enabling UVGI treatment outperforms the other surface treatment methods (italicised in the last column of the table), with the most beneficial outcome for high risk-high frequency scenario of 2%. It corresponds to the level of water saving potentials from UVGI treatment, which was found to linearly depend on the risk category and the frequency of application. This is in agreement with previous suggestion of UVGI effectivenss in environmental infection control in healthcare facilities (Memarzadeh et al. 2010). Further, owing to its significantly reduced treatment time averaging to approx. 10 mins per 500m^2, at company recommended UVGI-C dose of 220 J/m2 to achieve 99.9999% of SARS-CoV-19 removal) (UVGI Light Technology 2020), the UVGI treatment is also found to be suitable for rapid sanitisation to a clinical standard in high frequency scenario in high risk areas with low human occupancy during non-business hours, such as operation theatres, outpatient units, pathology labs, etc. We acknowledge the complexities of treating surfaces using a UVGI disinfection unit, specifically the limitation posed by surface type and human occupancy to achieve 100% disinfection. But as long as the total pathogenic load can be reduced substantially in high contamination zones by applying UVGI to the many surfaces that are readily exposed, this can be more effective than manual cleaning. In particular, such no-touch disinfection technologies would ensure occupational safety of the cleaning staff during a pandemic-like situation. Nevertheless, we accept that the role of manual cleaning at a lower frequency (at least once a day) would still be required to clean the dirt/dust and dead microorganisms, which otherwise will form a physical barrier, limiting the effectiveness of UV irradiation. Hence, all our estimates for UVGI treatment include manual dust removal from surfaces once a day.

Table 1
Surface area estimates of different non-residential assets suitable for UVGI-based sanitisation to reduce water demand in Mumbai

Category	Quantity	Reference
Total hospital sweep area[#]	8,138,580 m^2	Municipal Corporation of Greater Mumbai
Total education institute sweep area[#]	3,850,734 m^2	as above
Total commercial building sweep area[#]	7,387,737 m^2	as above
Publical transport sanitisation demand	75,000 m^2 (1500 buses)[†] 350,000 m^2 (@350 × 10 coaches suburban trains)[‡] 2,800 m^2 (7 × 4 coaches monorail)[‡]	Brihanmumbai Electric Supply and Transport (BEST) India Railways (Western) Mumbai Metropolitan Region Development Authority

*Typical urban household is assumed to be a unit family, comprising of 2 adults and 2 children

[#] Typical commercial building in Mumbai assumed to be comprising of 5 floors. Only 30% of the total available sweep area is assumed to be treated in this manner

[†] Assumed treated surface area, bus: 50m^2

[‡] Assumed treated surface area, coach: 100m^2

4.2. Case study analysis

Table 3 presents analysis of water-based sanitisation related freshwater demand in Mumbai, focusing on surface treatment requirements meeting the prevalent pandemic prevention best practice and recent WHO COVID-19 containment guidelines. The assessment of alternative/mitigative surface treatment measures for reducing the water demand has been based on the real-world data of existing non-residential assets in Mumbai (**Table 1 and Figure 3**). The estimated water demand for the corresponding city-scale surface treatment for the different categories using conventional surface sanitisation methods is shown in the 3rd column of **Table 3**. The last two columns respectively show the corresponding energy demand to operate the additional UVGI treatment units and the energy saving potential from the avoided water demand through this intervention. The assumptions applied to this evaluation are detailed in **Appendix 2** and **Table S2**.

Our evaluation estimated approximately 73 Million litres per day (MLD) of water requirement in Mumbai for surface sanitisation, if only water-based sanitisation methods are used (as per the protocols listed in **Table 3**). This is unsustainable, given Mumbai is already faced with a huge unmet freshwater demand under normal conditions, projected to be around 1100 MLD by 2021 (Safe water network 2016). Hence, if 50% of the earmarked surface treatments in non-residential settings could be replaced with alternative UVGI treatment units, this will lead to saving of up to 36 MLD freshwater. This water could then be diverted to meet the essential hygiene for the slum dwellers. The corresponding post-intervention SWI scores, indicitating the potential ward-level water footprint associated with public health related surface sanitisation in pandemic-like situation at city-scale is shown in **Figure 4** (smaller % values reflect greater intensity of UVGI treatment and conversely greater water saving potential for the corresponding wards). Typically, the wards across the south and extreme north part of the city having greater commercial and public assets (as shown in **Figure 3**, supporting data in **Table S1**) have much reduced water demand for the optimised sanitisation scheme, ranging between 0-30% of the total water demand for the conventional water-based sanitisation. These are associated with the reduced demands in transport hubs (wards A, B, D, E, F/S and G/S), commercial centres (A, P/S, R/C), Educational complexes (E, F/S, K/E) and healthcare facilities (F/S, K/W). On the other hand, with limited scope of integrating UVGI-based sterilisation, the estimated water

Table 2
Surface sanitisation water demand for 1000m^2 in different risk-appropriate hypotherical application scenarios. The corresponding SWI estimates are based on the UVGI replacement potential for each scenario, fulfilling the framework conditions.

Application category (Risk level -Frequency)	Scenario	Human occupancy (Vacant for > 1 hr)	Surface type	Treatment type	Original freshwater demand (l)	Optimised freshwater demand(l)	SWI (%)
High risk-High frequency (6 times/day)	Healthcare setting- patient ward	No/Yes	- Congested - Not air tight	Manual Cleaning and Chemical disinfection *	600	600	100%
	Healthcare setting- pathology labs	No/Yes	- Congested - Air tight	Mechanical spraying**	600	300	50%
	Hospital – outpatient units	Yes	- Exposed surface>10m	Manual cleaning and UVGI treatment	600	100	*2%*
Moderate risk-Moderate frequency (4 times/day)	Public transport – waiting areas	No/Yes	- Congested - Not air tight	Manual Cleaning and Chemical disinfection *	400	400	100%
	Public transport- bus	No/Yes	- Congested - Air tight	Mechanical spraying**	400	200	50%
	Public transport – rail coaches	Yes	- Exposed surface>10m	Manual cleaning and UVGI treatment	400	50	*3%*
Moderate risk-Moderate frequency (2 times/day)	Commercial/Institutional complex – small ventilated rooms	No/Yes	- Congested - Not air tight	Manual Cleaning and Chemical disinfection *	200	200	100%
	Commercial/Institutional complex – small sealed rooms	No/Yes	- Congested - Air tight	Mechanical spraying**	200	100	50%
	Commercial/Institutional complex – open plan rooms/ lobby areas	Yes	- Exposed surface>10m	Manual cleaning and UVGI treatment	200	25	*5%*

Surface wiped manually with clean water for removing dust and debris once daily (assumed water usage: 0.01l/m^2).
Treatment protocols:
* Floor and equipment wiped with 5g/l hypochlorite solution disinfectant; frequently touched surfaces wiped with 75-90% ethanol disinfectant (assumed water usage: 0.1l/m^2) (Kampf et al. 2020).
** Surface sprayed with 1g/l hypochlorite solution disinfectant; frequently touched surfaces wiped with 65-75% ethanol disinfectant (assumed water usage: 0.05l/m^2) (Rutala & Weber 2014).

demand in wards with large residential population (F/N, K/E, L, P/N, N, S) still remains high, ranging between 45-75% of the conventional water-based sanitisation.

The net energy tradeoff from this alternative sanitisation scheme is estimated as 13 MWh electricity demand per day. This is estimated using the company recommended sanitisation guidelines of the the UVGI-treatment units, the corresponding additional electricity demand to operate the units is estimated as 28 MWh; however, this allows saving of around 15 MWh electricity associated with the water treatment energy demand (shown respectively in the 4th and 5th columns in **Table 3**). Further, it reduces the requirement for chemical disinfectants, liquid chlorine, chlorine dioxide, and sodium hypochlorite, which are commonly used in chemical treatment of human-enteric viruses in contaminated wastewater (Lizasoain et al. 2018). The other advantage of dry sanitisation of hospital surfaces using UVGI radiators is to reduce the risk of contamination of the drainage system as waste-water discharged from a COVID-19 designated hospital have been found to be SARS- CoV-2 RNA positive (Wang et al. 2020).

The insights from Mumbai can be applied to larger city regions elsewhere in the world with similar water demand for water-based surface treatment. Our assessment demonstrates that the disinfection of large surfaces can be efficiently conducted with UVGI treatment, significantly reducing the treatment time and consumption of traditional spray and other chemicals. Water management is one of the key issues ensuring sustainable social wellbeing in water-deficient cities and the demonstration case study is providing some pertinent evidence towards innovating this practice in the future, both while handling any pandemic like situation or for transforming the city-scale water footprint for targeted public health requirements. Overall, our case study shows that wider uptake of the UVGI-based technology in non-residential asset sanitisation has the potential to offer huge saving on city-scale water resources, allowing better use of clean water for essential human consumption and hygiene maintenance in deprived/informal communities.

Based on the evaluations of additional energy demands and the potential gains (water resource and energy savings), our study found UVGI to be the most effective for high frequency sanitisation in high-to-moderate risk applications, such as healthcare facilities, public transit, transport hubs, etc.

4.3. *Cost-benefit assessment for different sanitisation methods*

A cost-benefit analysis of three sanitisation methods - Manual surface wiping, Mechanical cleaning (Rapid disinfectant sprayer) and UVGI cleaning - are presented in **Table 4**. In the analysis the treated area is kept common at 1000 m^2; costs and benefits are respectively shown as -ve and +ve. Overall disinfecting costs were based on a published online disinfecting costs calculator tool (Midwest 2021). The key costs include labour, chemical, capital (for any instrumentation) and energy (for operating instruements). The relevant sources of information used in the analysis are provided in the footnotes below the table. The benefits for replacement of conventional sanitisation with UVGI treatment method considers cost-saving on chemical and water demand and labour. The cost-benefit also includes marginal water demand (10% of the original) for periodic wiping of a contaminated surface in an effort to maintain the clean appearance of the surface as well as to reduce the accumulation of dust/debris, dead microorganisms and other deposits which may produce physical barrier, thereby limiting the effectiveness of the UV irradiation.

We acknowledge the UVGI-treamtment technologies would involve resource and energy demand in their manufacturing but we assume these will be incorporated in their one-off capital costs, hence not considered separately. The capital cost for UVGI unit makes it

Table 3
Estimation of the potential for offsetting common water-based surface sanitisation demand with UVGI-based surface treatment in Mumbai. The corresponding energy demand for running the alternative treatment and the potentials for energy saving for production of clean water are shown in last two columns (italicised).

Application category	Current water-based sanitisation protocol (Application frequency in brackets)	Freshwater demand (Million l/Day)*	Additional energy demand for UVGI unit operation (MWh/day)**	Energy saving from avoided clean water demand (MWh/day)#
High risk, High frequency - Critical healthcare facilities: Surface cleaning	floor wiped with 5g/l hypochlorite solution (6 times/day) frequently touched surfaces wiped with 90% ethanol (6 times/day)†	*49*	*11*	*10*
Moderate risk, Moderate frequency - Public transit (10 coach suburban trains): Surface cleaning	floor wiped with 1g/l hypochlorite solution (2 times/day) frequently touched surfaces wiped with 70% ethanol (4 times/day)‡	*1.4*	*0.5*	*0.3*
Moderate risk, Moderate frequency - Public transit (4 coach monorail): Surface cleaning	floor wiped with 1g/l hypochlorite solution (2 times/day) frequently touched surfaces wiped with 70% ethanol (4 times/day)‡	*0.01*	*0.004*	*0.002*
Moderate risk, Moderate frequency - Public transit (BEST buses): Surface cleaning	floor wiped with 1g/l hypochlorite solution (2 times/day) frequently touched surfaces wiped with 70% ethanol (4 times/day)‡	*0.3*	*0.11*	*0.06*
Moderate risk, Low frequency - Educational institutes: Surface Cleaning	aerial mist spray with 1g/l hypochlorite solution (2 times/day) surface wiped with 70% ethanol for non-corrosion resistance (2 times/day) ‡	*8*	*5*	*2*
Moderate risk, Low frequency - Commecial: Surface cleaning	aerial mist spray with 1g/l hypochlorite solution (2 times/day) surface wiped with 70% ethanol for non-corrosion resistance (2 times/day) ‡	*15*	*10*	*3*
Total		***73***	***28***	***15***

* For detailed calculations on the population and area parameters refer to Supplementary section, Table S2

** Each unit has electrical power of 700 W, including 8xUVGI-C germicidal tubes, with rechargeable zap of 2-2.5 hours (approx. 500 m^2, equal to 9-10 rooms, average 10-minute treatment time per room at company recommended UVGI-C dose of 220 J/m2 to achieve 99.9999% of SARS-CoV-19 removal) (UVGI Light Technology 2020)

\# Estimated energy use per litre of wastewater treatment, water pumping and delivery in India of 0.4 Wh/l. Miller et al. (2013). Only 50% of the water demand is included in the energy demand estimation for a conservative estimate.

† (Kampf et al. 2020)

‡ (Rutala & Weber 2014)

unattractive in the first year (as indicated in **Table 4**, the net cost-benefits calculations at the end). However, accounting for the annual benefits accrued, the UVGI system starts giving positive return on investment from the 2nd year onwards, surpassing the annual costs for the corresponding manual or mechanical treatment options. Further, it would reduce the dependence on chemical disinfectants, liquid chlorine, chlorine dioxide, and sodium hypochlorite, which are commonly used in chemical treatment of human-enteric viruses in contaminated wastewater (Lizasoain et al. 2018). The other advantage of dry sanitisation of hospital surfaces using UVGI is to reduce the risk of contamination of the drainage system as waste-water discharged from a COVID-19 designated hospital has been found to be SARS- CoV-2 RNA positive (Wang et al. 2020). It is noteworthy that any such estimation involves uncertainties but our estimation of energy demand for water treatment is a conservative estimate and accordingly, the energy saving potential is likely to be much higher, making the alternative sanitisation scheme even more attractive.

5. Limitations for UVGI-cleaning and recommendations

As identified in the cost-benefit analysis, the key drawbacks with UVGI light disinfection relevant to wider implementation in developing countries include the initial costs, the time associated with the process, running costs (periodic maintenance, electricity and training costs for safe instrument handling (Hom 2020). Further, UVGI irradiation is affected by shadowing, contaminants, and distance from a source, as well as the duration of irradiation and power of the source. Due consideration needs to be given to these issues, which could be overcome through adequate training of the operators in these countries through the manufacturers and their local representatives.

Since the onset of the COVID-19, several cities are taking the lead in cleaning methods and service changes to help stop the spread of the coronavirus. The Chicago Transit Authority (CTA) purchased innovative electrostatic sprayers that apply disinfectant to all surfaces of buses and rail cars. Worn like backpacks, these electrostatic sprayers allow workers to deep clean 300 of these vehicles every night. During times of service operation, workers routinely clean commonly touched areas of

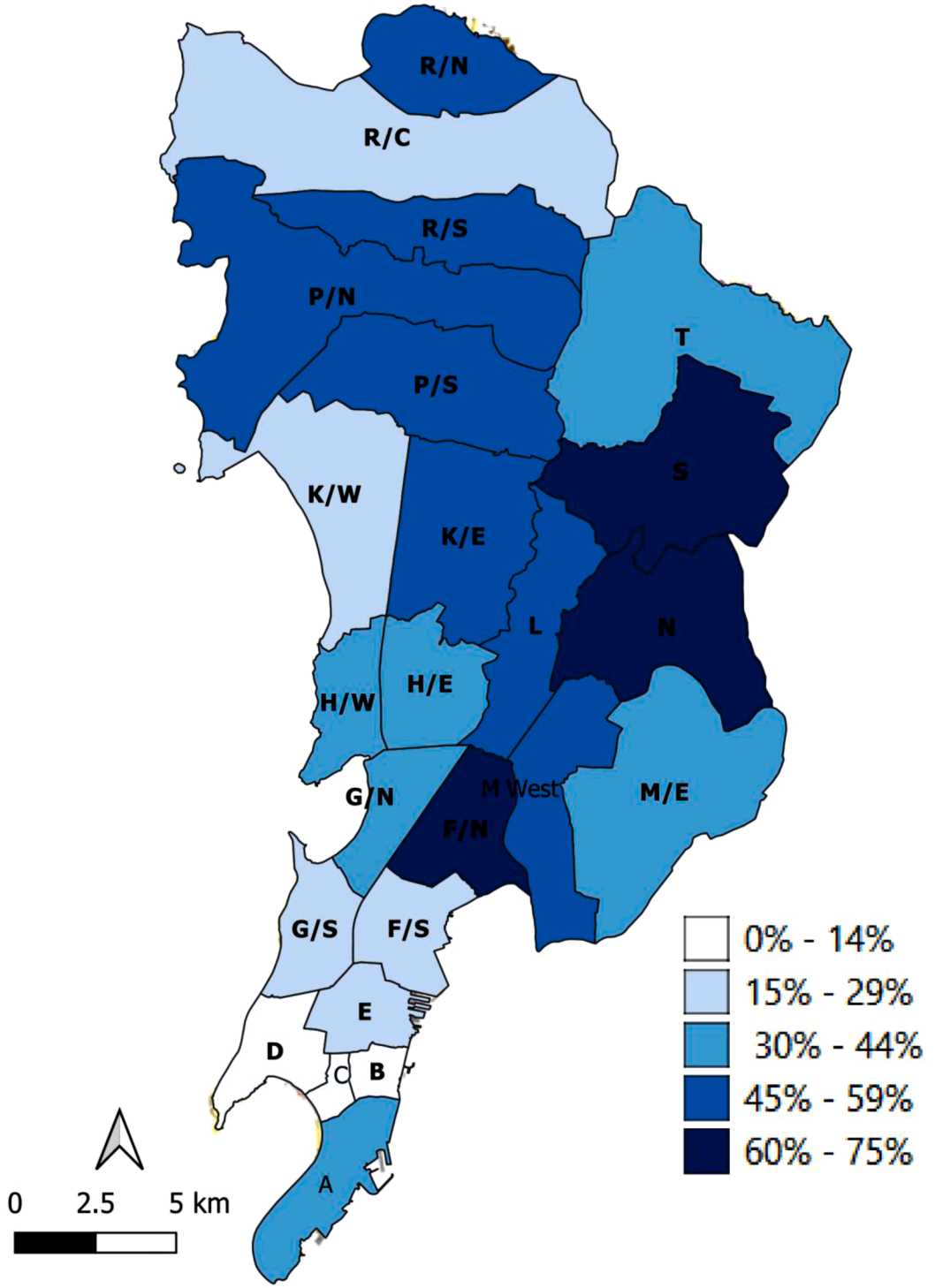

Figure 4. Projected ward-level SWI scores, indicating optimised water footprint for the modified surface sanitisation integrating UVGI treatment relative to the traditional water-based sanitisation in Mumbai (smaller % values reflect greater intensity of UVGI treatment and conversely greater water saving potential for the corresponding wards).

the vehicles by hand (CTA 2020). New York's Metropolitan Transit Authority (MTA) has taken similar steps as Chicago's CTA with the use of electrostatic sprayers; additionally, the MTA is researching the effectiveness of UVGI light and new air filters to kill bacteria and viruses (MTA 2020). Sanitation stations and daily deep cleaning of public transit vehicles were not the norm prior to COVID-19 and may just be temporary stop-gap measures. The purchase of electrostatic sprayers and city officials researching and investigating the efficacy of antimicrobial materials, air filters, and UVGI lighting suggest some thought to the future. These measures could become permanent pending cities' willingness and/or ability to budget for these items in the long-term. However, political, cultural, and budgetary landscapes of cities may dictate adoption of these public health measures.

While the proposed UVGI integration is timely for facilitating increased automation in techno-centric, smart cities around the world, such interventions may meet resistance from labour groups in several

Table 4
Cost-benefit analysis comparing conventional sanitisation practice of manual and mechanical cleaning to UVGI-based disinfection (note: costs are in Indian currency).

Total costs (after 1 year))	Manual surface wiping	Mechanical cleaning	UVGI cleaning	**Total benefits (after 1 year)**	
Surface to be cleaned (m2/day)	1000	1000	1000		
Disinfectant solution demand (per m2)	0.0033	0.0033			
Solution needed (l)	3.27	3.27			
Cost per litre (IRs)	1000	1000			
Solution cost (IRs)	-3265.16	-3265.16		Chemical saving	3265.16
Water requirement (l)	100[†]	100	10		
Water rate (IRs/l)	0.2	0.2	0.2		
Water cost (IRs)	-20	-20	-2	Water cost saving	18
Area covered per staff (m^2)	200	1000	1000		
Staff required	5	1	1		
Wage rate (IRs/day)	100	150	300		
Wage cost	-500	-150	-300	Wage saving	200
Recurring costs (Electricity, kWh)		-2.172[*, #]	-7.602	Avoided energy cost for reduced water demand	0.04
Annual costs	-1381583.28	-1254626.06	-113004.73	Annual benefits	1271367.55
One-off Equipment cost	0	-80227[*]	-1424525		
Net Cost-Benefit (after 1 year)	*-1,381,583.28*	*-1,334,853.06*	*-266,162.18*		
Net Cost-Benefit (after 2 year)	*-2,763,166.56*	*-2,589,479.12*	*892,200.64*		

Note – IRs: Indian Rupees; Currency exchange applied: 1 GB pound = 100 IRs; 1 US dollar = 73 IRs
Assumptions:
[†] Surface treatment water usage – 0.1l per m^2
[*] Disinfectant sprayer spec - FG-SSHP20-Cordless 20V Ion battery/42oz sprayer $1,099 per unit. Max 2.0 ah Lithium-Ion batterie
[#] Average cost of state electricity supplied in India: 5.43 IRs per kilowatt hour (Statista 2019)

cities. Specifcially, in developing countries with abundant low-cost labour, there is always some concern about employment implications of automated solutions. An automated UVGI system can easily displace jobs of several cleaners, that can adversely affect the livelihoods of low-wage earners. The labour unions may oppose mass adoption of such systems. Mobilising finance for a large-scale adoption of such a system could also be a challenge for health authorities. Further, this requires adequate risk assessment prior to implementation to protect people from harm, as well as training the staff for safe operation of the instruments. For UVGI treatment in commercial buildings, horizontal skyscraper designs would become more practically suitable (Margolies 2020). For example, Vanke Center mixed-use building in Shenzhen, China is a prime example of the horizontal skyscraper design (it is as long as the Empire State Building is tall and floats above a manicured campus on several large columns).

Future integration of the UVGI-cleaning hardware with localised renewable energy generation to fulfil the energy demand through evidence-based professional design and installations would further improve the sustainability of the intervention measure. A chemical-free low-cost, solar-powered mobile UVGIGI disinfection unit has already been prototyped to disinfect a wide range of microorganisms (bacteria and fungi, and viruses including the actual SARS-CoV-2 (Mahammedi & Mahammedi 2020). More work is indeed required to develop some best practice in performance and energy efficiency of this integrated approach and appropriate use of the UVGI technology through real-world feasibility assessment, specifically to alleviate the dependence on precious water resources in developing countries. In addition, appropriate procedures for maintenance and disposal of lamps need to be implemented, and health-care workers must be trained in the use of UVGI.

In order to overcome the water and resource requirement for chemical-based sanitising methods, alternative solar-powered mobile UVGI disinfection units are already being developed. These units combine the advantages of using abundant solar energy and UVGI disinfection capabilities, offering complete autonomy for off-grid applications through the built-in photovoltaic (PV) system that includes a solar panel (Mahammedi & Mahammedi 2020).

6. Conclusions and further work

This paper evaluated a methodological framework for reducing city-scale water footprint in sanitisation of non-residential assets through a mix of three sanitisation measures (Manual surface wiping, Mechanical cleaning/Rapid disinfectant sprayer, Ultraviolet germicidal irradiation, UVGI treatment) in terms of a Sanitisation waterfootprint index (SWI). The following are the main conclusions from this work:

- SWI can range between 0-100% (lower score representing more aggressive application of UVGI-based sanitisation, leading to reduced water demand from the corresponding intervention).
- The hierarchical conditional steps in the framework determine which of the three methods of surface sanitisation could be the most applicable in a given setting.
- Preliminary evaluation of the framework based on a number of hypotherical scenarios shows the SWI for the setting allowing UVGI treatment outperforms the other surface treatment methods, with the most beneficial outcome for high risk-high frequency scenario with SWI as low as just 2%.
- Demonstration of the framework using ward-level spatial analysis in Mumbai, India, a water deficient city, estimates SWI ranging between 0-30% in those wards with greater commercial and public assets. This shows clear merit of this framework in re-configuring city-scale public health sanitisation water footprint, with potential for reducing fresh water demand by 36 Million litres per day (MLD), if 50% of Mumbai's non-residential surface sanitisation (including healthcare facilties, schools, offices, public transit (buses, local trains) could be conducted via alternative UVGI treatment units. The corresponding energy tradeoff for this scheme scheme is estimated as 13 MWh electricity demand per day (28 MWh required for operating the UVGI treatment units, 15 MWh electricity savings from reduced water treatment energy demand).
- Based on the evaluations of additional energy demands and the potential gains (water resource and energy savings), our study found UVGI to be the most effective for high frequency sanitisation in high-to-moderate risk applications, such as healthcare facilities, public transit, transport hubs, etc.
- The cost-benefit analysis conducted to assess the tradeoffs of UVGI sanitisation technology acknowledges one-off capital investments and running costs, including periodic maintenance, electricity and training costs (the latter towards safe instrument handling). However, their long-term benefits beyond 2nd year of operation in terms of resource and energy savings for producing water and disinfection grade chemicals, as well as for improving the accesibility to clean water and public health in deprived/informal parts of a city, make

them more favourable as a viable alternative to 100% water-based sanitisation.

Wider implementation of this framework holds potential for reconfiguring water resources for reliable/regular supply in domestic settings during future infectious disease outbreaks at city-scale. Besides, this intervention can foster strategic transformation of cityscale water footprint, which is deemed essential for ensuring sustainable growth of water deficient cities globally. Integrating UVGI treatment with localised renewable energy generation could further strengthen water and energy/resource independence in non-residential asset sanitisation, leading to chemical-free sustainable growth of cities.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We would like to acknowledge the funding through the UK Royal Academy of Engineering to the Newton-Khalidi Industry-Academic Partnership (Grant no. IAPP18-19\177) vide the contributions from the UK Department for Business, Innovation, and Skills.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.scs.2021.103268.

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